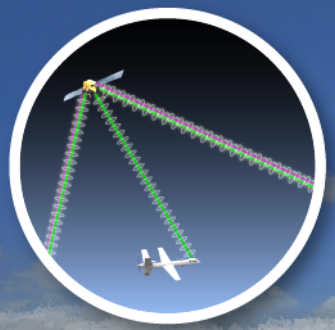


Low C-SWaP Well Clear Trade Study
Preliminary Results

Gilbert Wu
Seungman Lee
Devin Jack

Objectives

- Investigate trade space for Detect and Avoid (DAA) Well Clear definition for UAS with low cost, size, weight, and power (Low C-SWaP) sensors that detect and track non-cooperative aircraft
- Recommend candidate DAA Well Clear (DWC) definition(s) for the SC-228 to consider

Scope of DWC Applicability

- Between non-cooperative aircraft and UAS with low C-SWaP sensors that are
  - Below 10,000 ft and above 500 ft AGL
  - During extended operations in classes D, E (non-terminal), or G (non-terminal), or
  - During transit operations in classes B and C
  - For UAS within a certain speed range

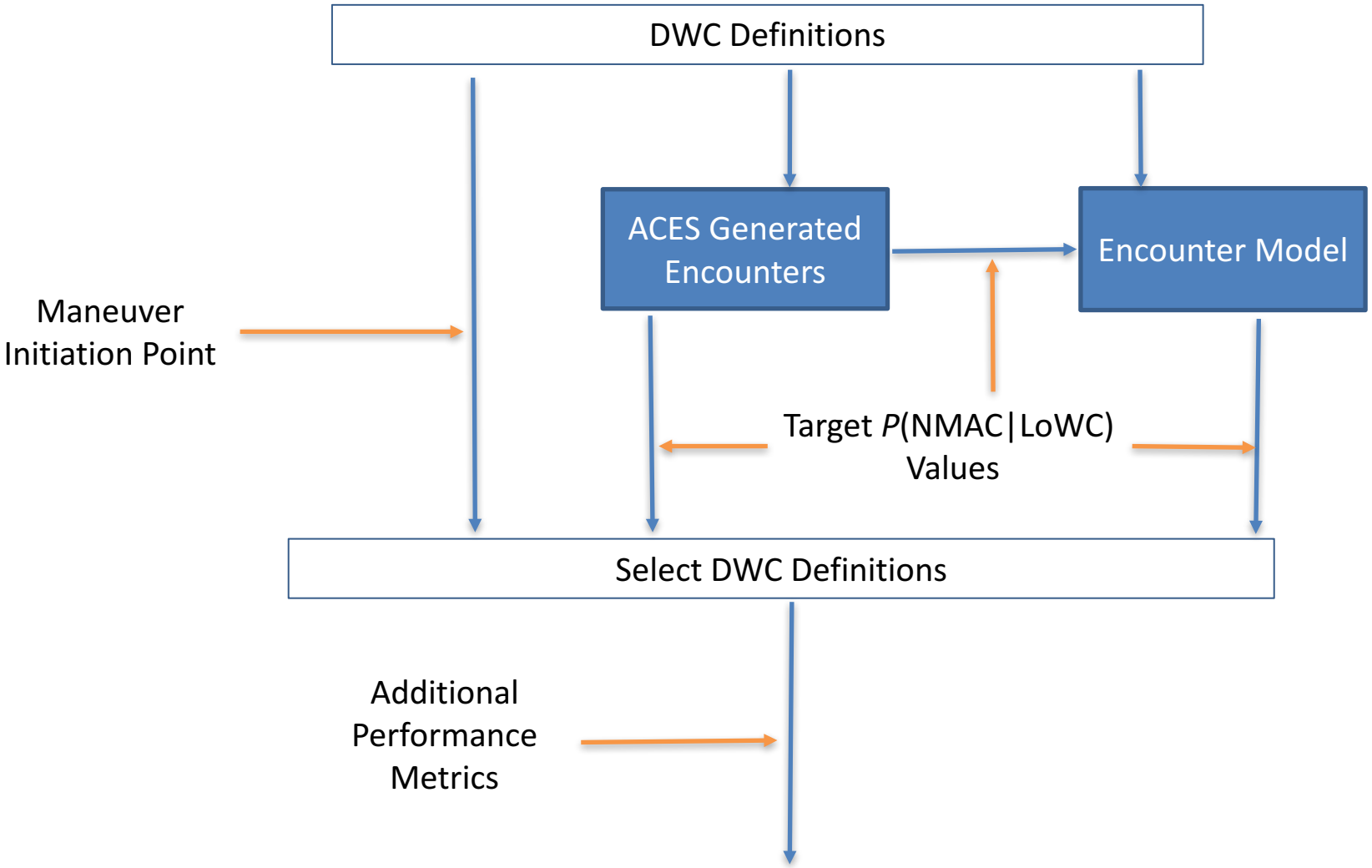
Schedule

- **Preliminary Results: December 5, 2017 at SC-228 F2F**
- Final results: February 20, 2018

Performance Metrics

- **Unmitigated collision risk**
  - The probability of a near mid-air collision (NMAC) given a loss of DWC
  - Denoted as P(NMAC|LoWC)
- **Maneuver initiation point**
  - Latest point for ownship to maneuver to maintain DWC
- Bearing, elevation, range, and closure rate distribution of intruders at the Loss of Well Clear (LoWC)
- CPA miss distance/time given LoWC

Selection Workflow



DWC Definitions

- DWC types and threshold values (* for threshold)
  - **DWC1: h*, HMD*, modTau***
  - DWC2: h*, HMD*, t_{pz}*
  - DWC3: Static hockey puck: h*, R*
  - DWC4: Dynamic hockey puck: h*, R*(rdot) = a* + rdot x b*

Type	h* (ft)	HMD* (ft)	modTau* (sec)
DWC1	450	[1000, 9000]	[0, 35]

Type	h* (ft)	HMD* (ft)	Tpz* (sec)
DWC2	450	[1000, 9000]	[0, 35]

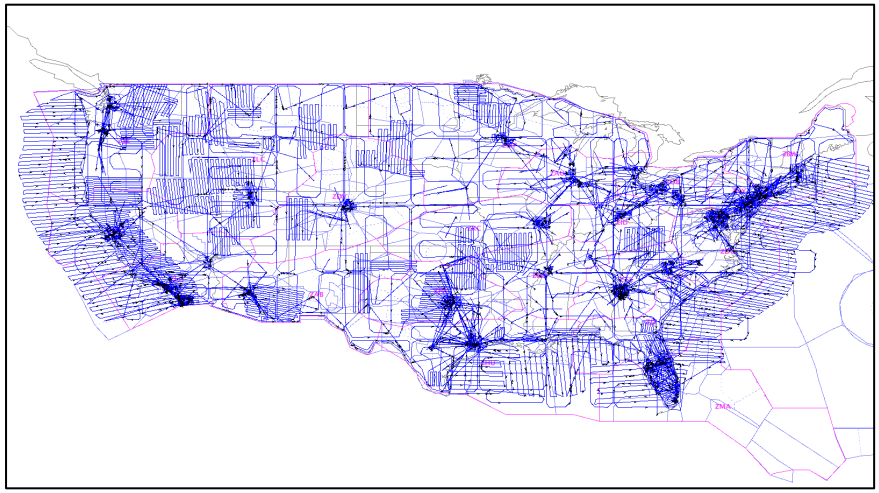
Type	h* (ft)	R* (ft)	
DWC3	450	[1000, 9000]	

Type	h* (ft)	a* (ft)	b* (sec)
DWC4	450	[1000, 6000]	[0, 20]

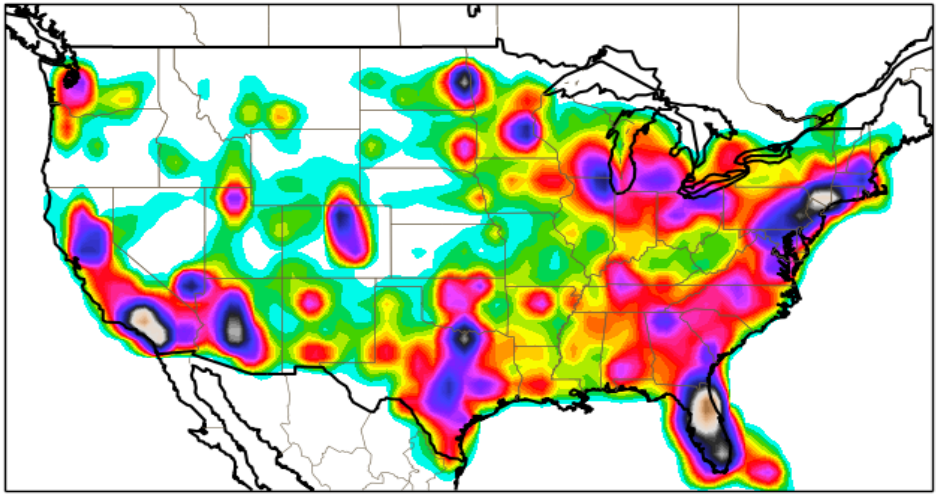
ACES Generated Encounters

ACES Encounters Considered

- 3.3 million encounters
  - between projected UAS trajectories and recorded VFR traffic from 21 days in year 2012
  - Cooperative aircraft regarded as surrogates of non-cooperative
- About 60% of the encounters are considered “low C-SWaP”
- 708 NMACs (for low C-SWaP)
- Number of LoWCs varies

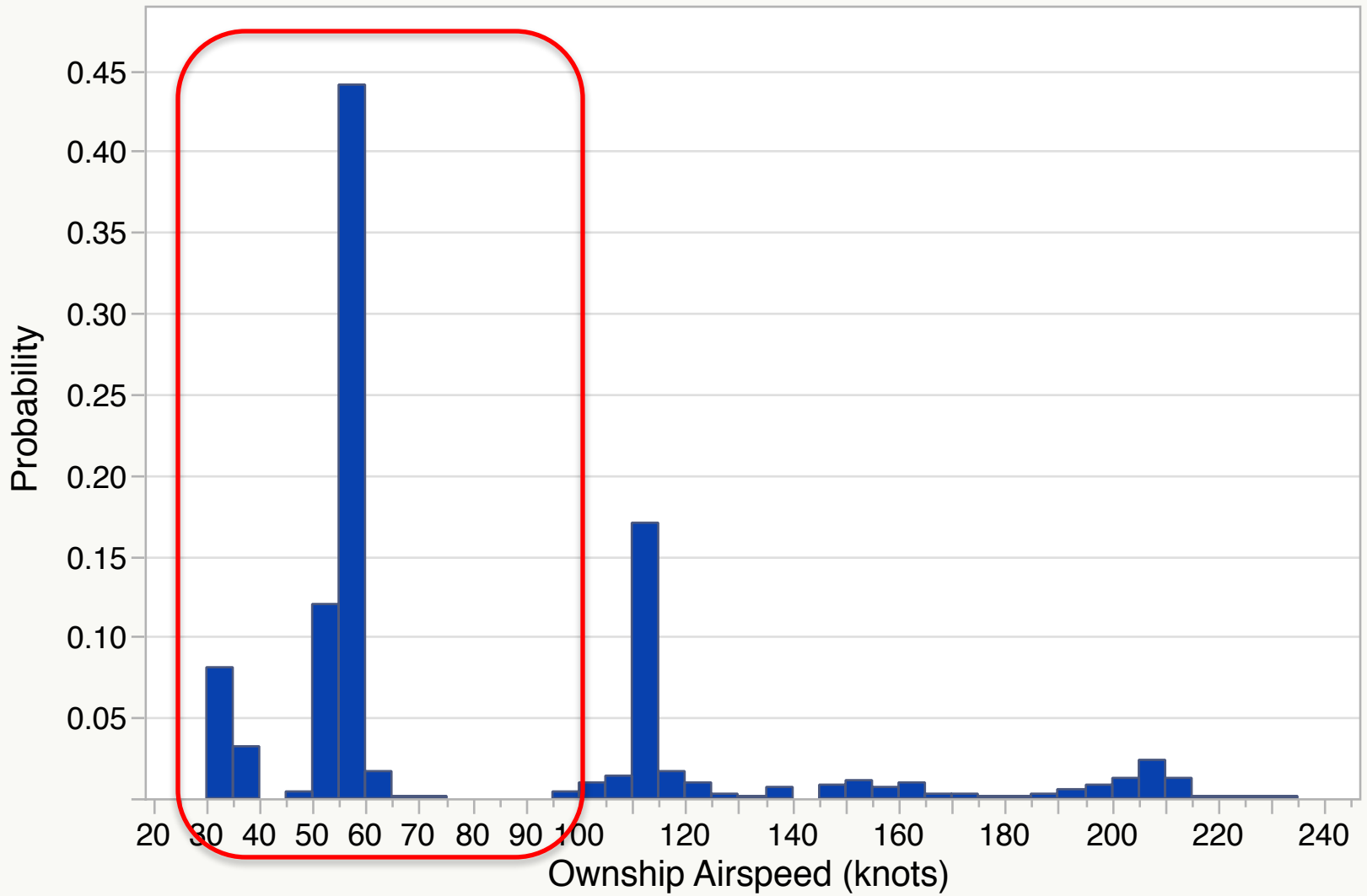


UAS

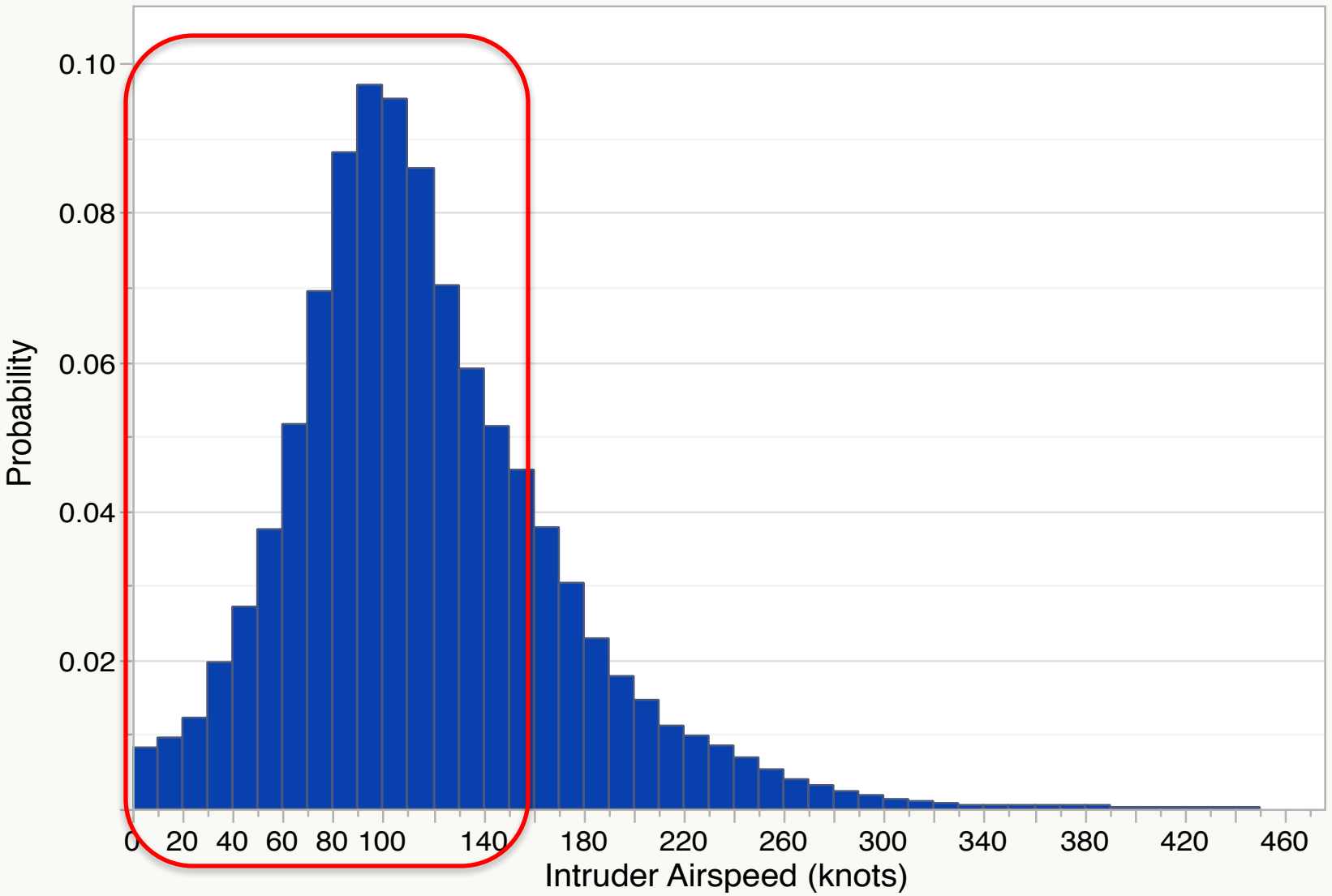


VFR

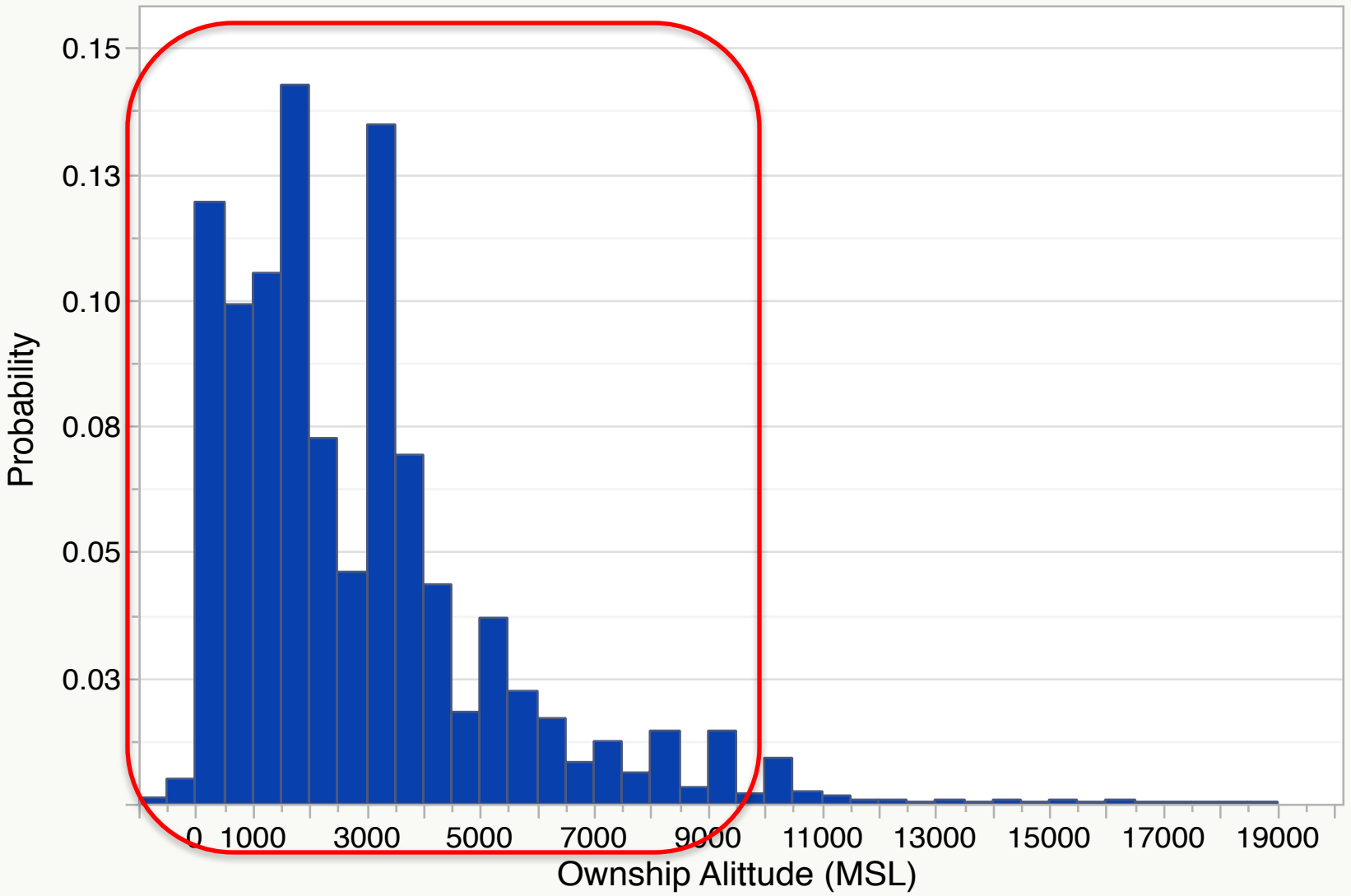
Speed Distribution of Ownship



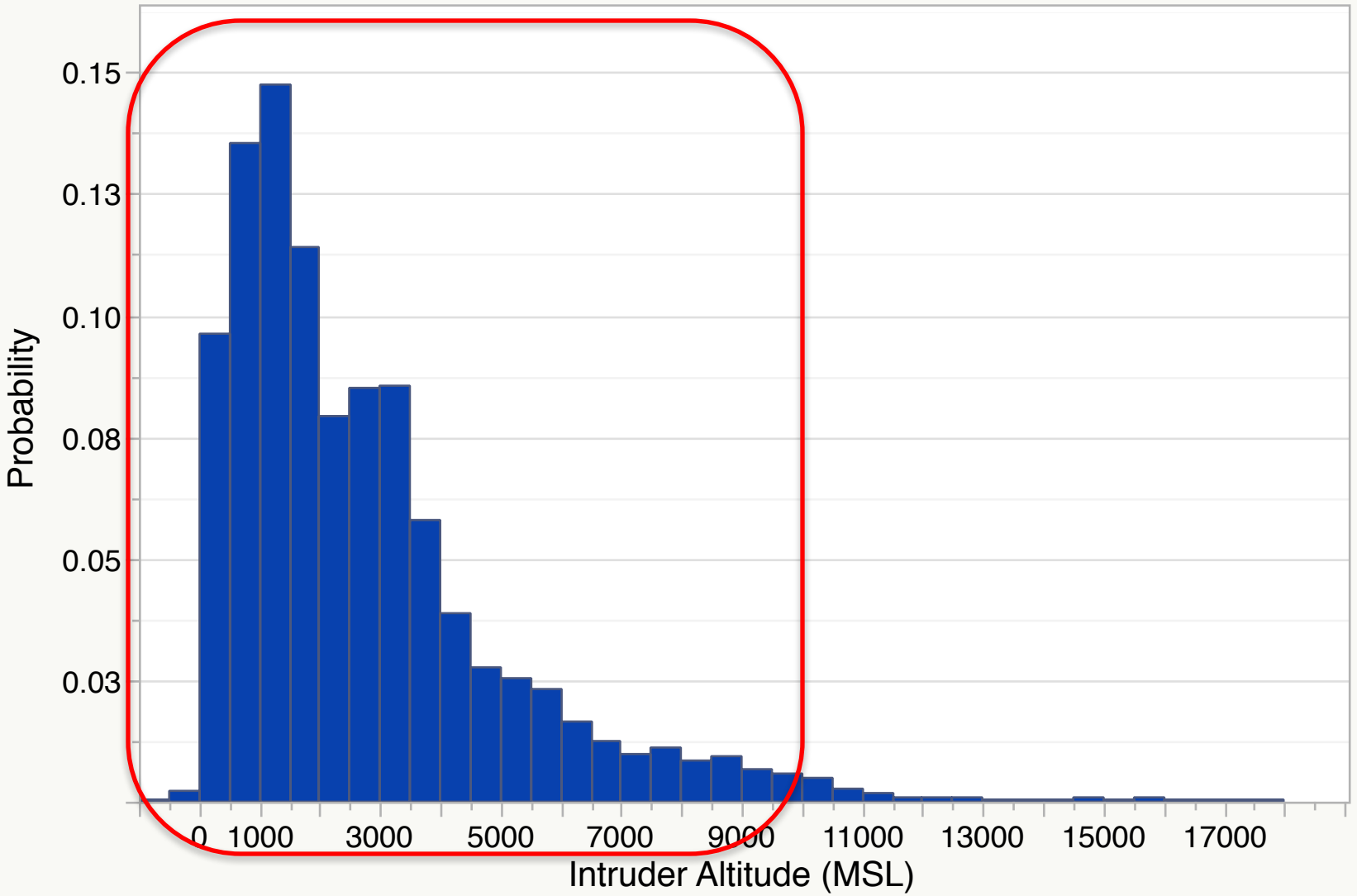
Speed Distribution of Intruder



Altitude Distribution of Ownship



Altitude Distribution of Intruder VFR Aircraft



Experimental Matrix

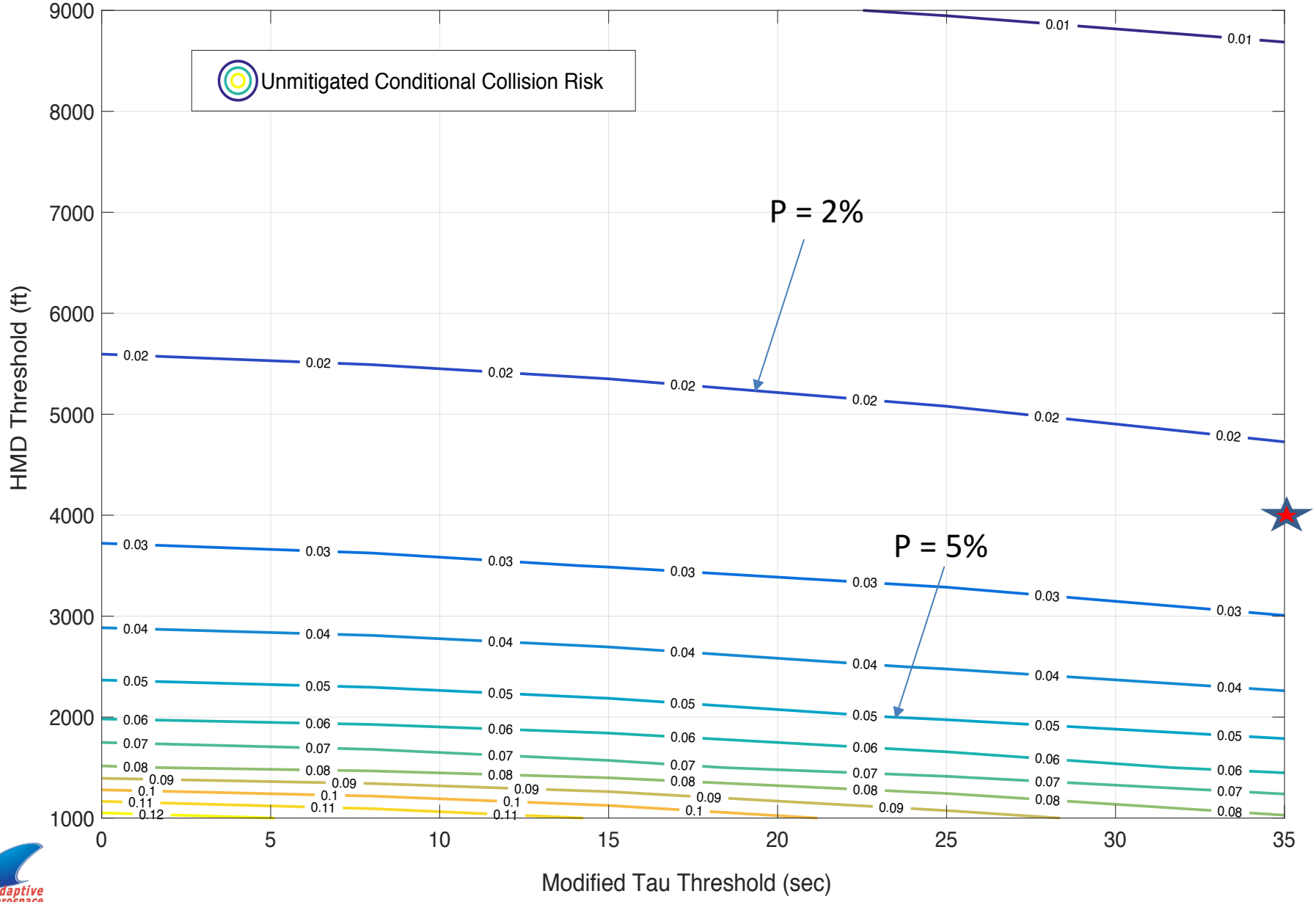
- **Modified Tau DWC**
  - Total 45 settings
  - ModTau threshold (5 levels): 0, 8, 15, 25, 35 (sec)
  - HMD threshold (9 levels): 1000, 1500, 2000, 2500, 3000, 3500, 4000, 6500, 9000 (ft.)
  - Altitude threshold (1 level): 450 (ft)

- Time to Protected Zone (TPZ) DWC
- Static Cylinder DWC
- Dynamic Cylinder DWC

Target Metric Values

- P(NMAC|LoWC) is between 2% and 5%
  - Phase 1 P ~ 2.2%
  - Previous Lincoln Lab work recommended 5%
- Maneuver initiation point range as small as possible

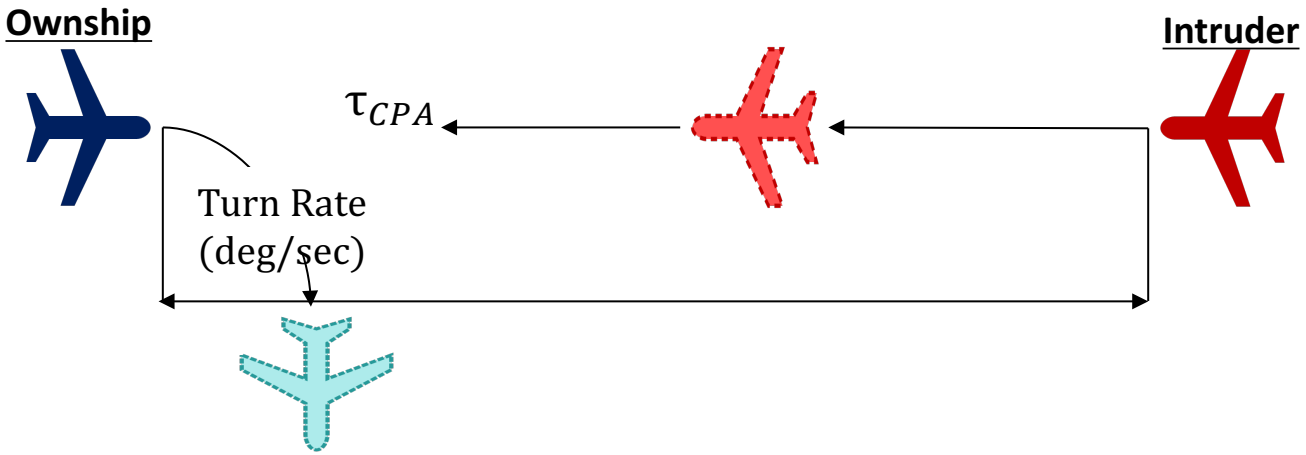
Unmitigated Collision Risk P(NMAC|LoWC)



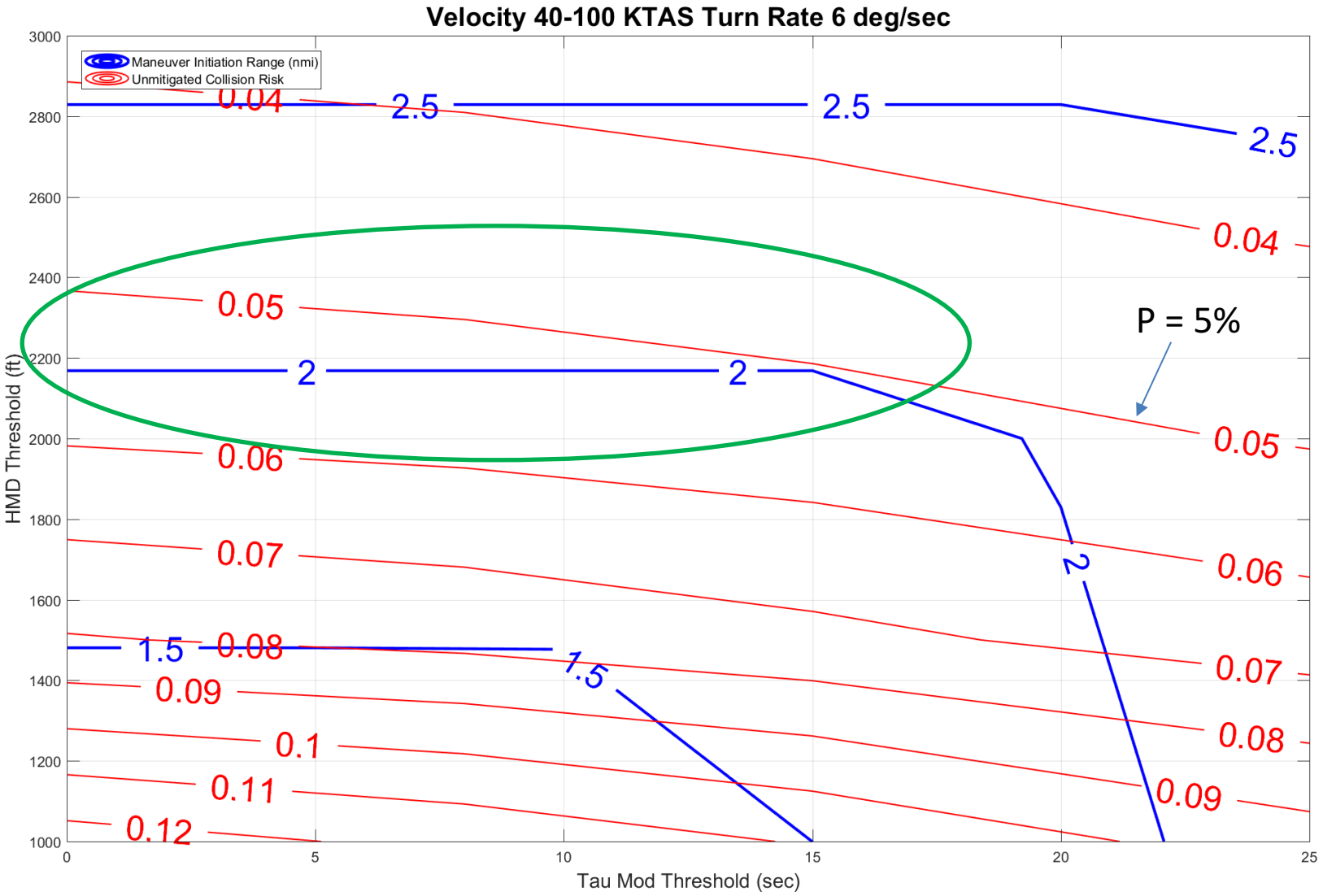
Maneuver Initiation Point

Maneuver Initiation Point

- 2PAIRS
- Head-on, co-altitude encounter
- Only horizontal maneuver is considered
- Constant roll rate, steady-state turn rate, ownship speed, and intruder speed
- $range \quad = f\ (DWC,\ \ ownship\ speed,\ \ intruder\ speed)$
- UAS (Ownship) speed 40 to 100 kts
- Turn rate 6 deg/s (3 and 12 deg/s results also looked at)



“Sweet Spot”


Velocity 40-100 KTAS Turn Rate 6 deg/sec
Maneuver Initiation Range (nmi)
Unmitigated Collision Risk
HMD Threshold (ft)
Tau Mod Threshold (sec)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
0
5
10
15
20
25
0.04
2.5
2.5
2.5
0.04
0.05
2
2
P = 5%
0.05
0.06
2
0.06
0.07
1.5
0.08
1.5
0.07
0.09
0.08
0.1
0.09
0.11
0.12

Summary

- "Sweet spot" HMD* 2000 to 2500 ft, modTau 0 to 15 sec
  - P(NMAC|LoWC) ~ 5%
  - Maneuver initiation range ~ 2 nmi (given 6 deg/s turn rate)
  - Compared to low C-SWaP radar range that may be below 3 nmi
- To further reduce range requirements, we may
  - Go above 5% for P(NMAC|LoWC)
  - Require a higher turn rate at 40 kts (e.g., 12 deg/s)
  - Increase minimum ownship speed from 40 kts
  - Mandate a minimum turn speed > 40 kts for ownship
- Other considerations
  - Range and bearing distribution trade-off

Next Steps

- ACES encounter analysis
  - Apply additional filters
  - Analyze additional performance metrics
  - Analyze results from other DWC types
  - Analyze results from Phase 1 UAS (speed and altitude)
- Encounter model
  - Parallel work to ACES analysis
  - Comparison to ACES results for validation
- Candidate DWC definitions for further evaluations
  - May propose more than one (possibly two) definitions varying by P values
- Fast time simulation 2 for alerting and sensor (May 2018)
- HITL for low C-SWaP (Nov. 2018)

Backup Slides

Encounter Model

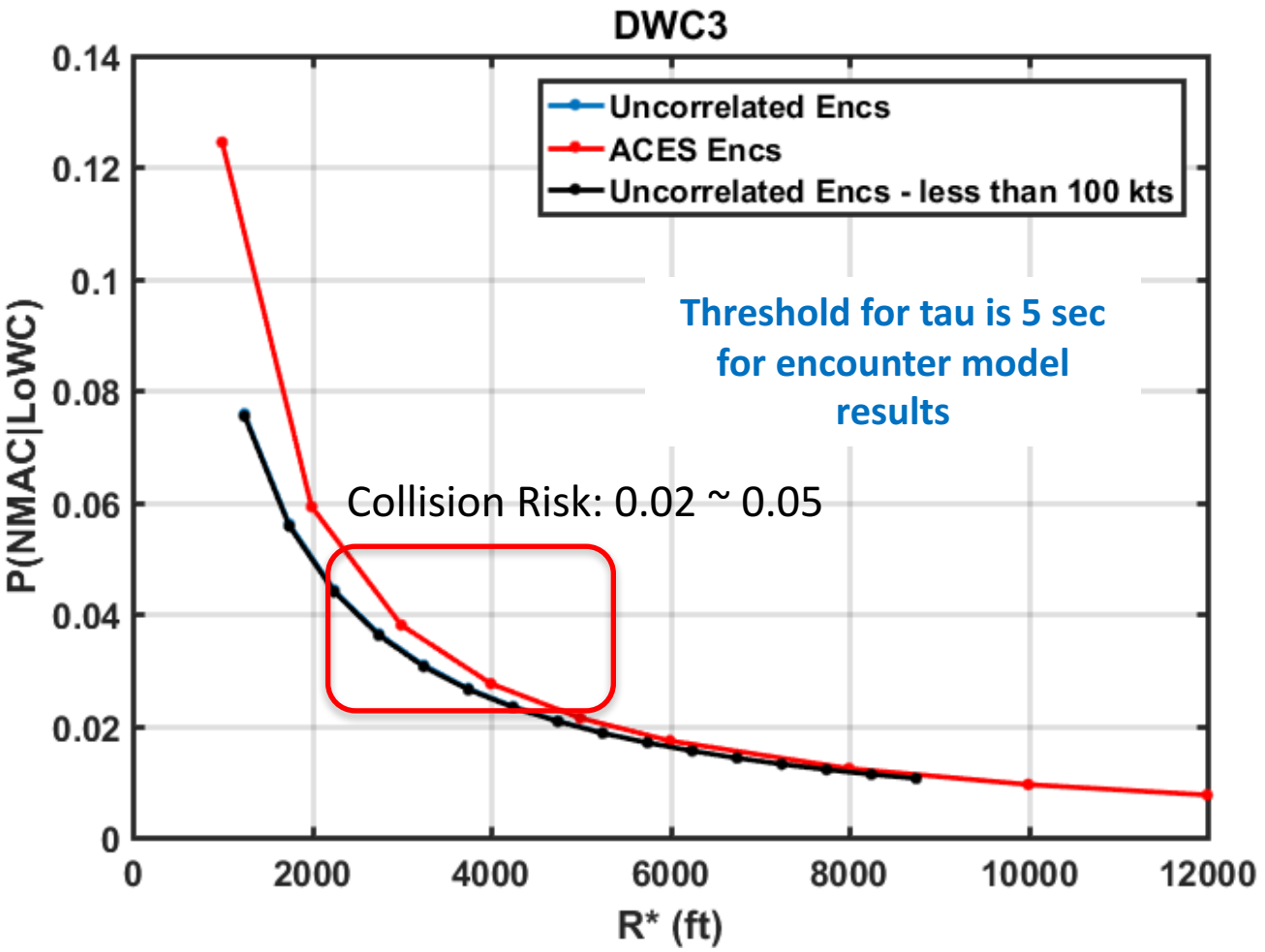
Uncorrelated Encounter Model

- Assumptions
  - Phase 1 VFR traffic
  - Same encounter set used to define SARP WCV definition
    - Enables comparison with previous results
  - Encounters are between two aircraft, where one or both aircraft do not have transponders, or both are VFR (1200 code)
  - Looking at full encounter set (<300 kts) and subset of encounters with speeds < 100 kts

Results are preliminary. No conclusions should be drawn from the results until they can be further analyzed and understood.

Preliminary Comparison Results

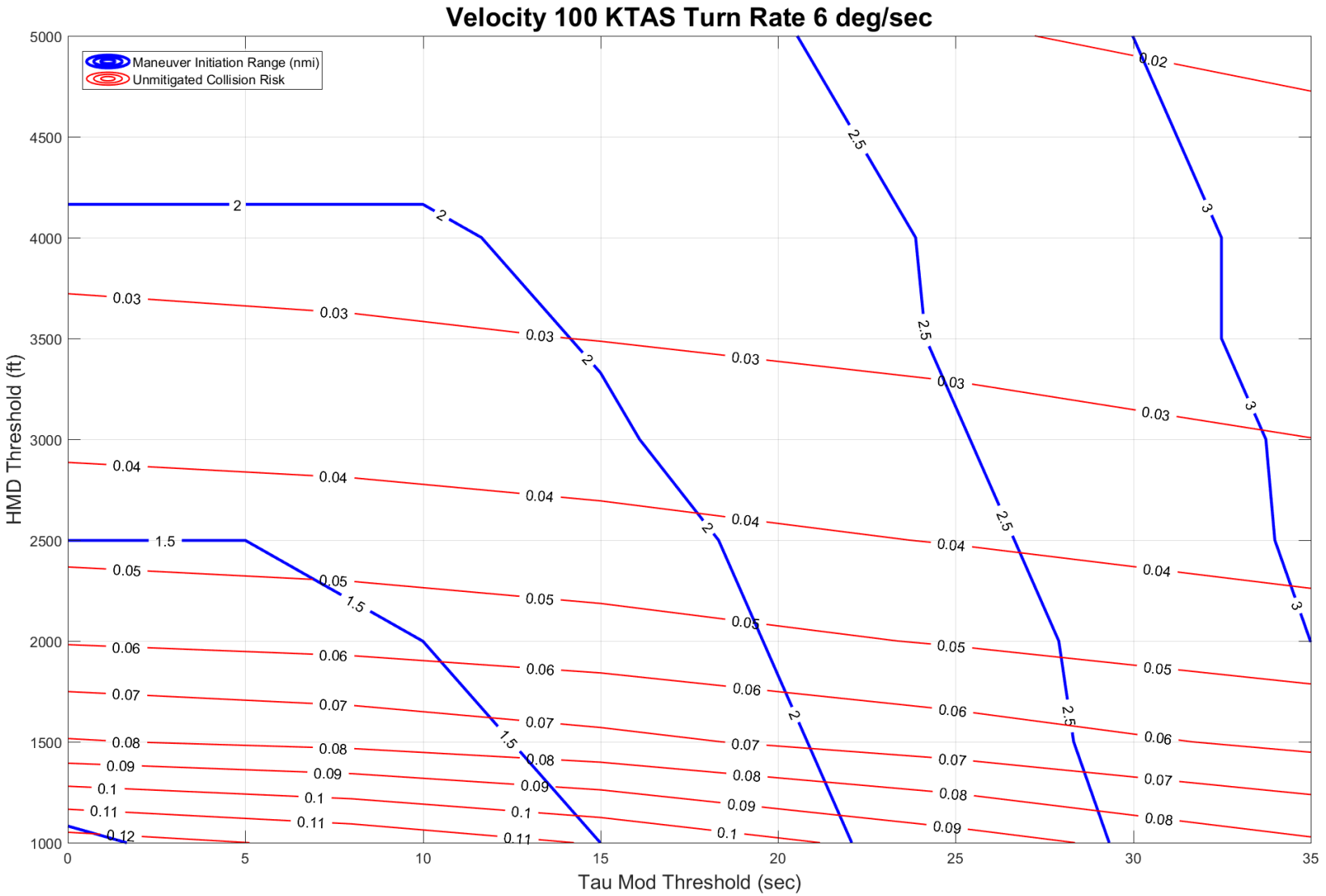
- DWC3
  - P(NMAC|LoWC) vs. R* using ACES
  - P(NMAC|LoWC) vs. R* using the encounter models

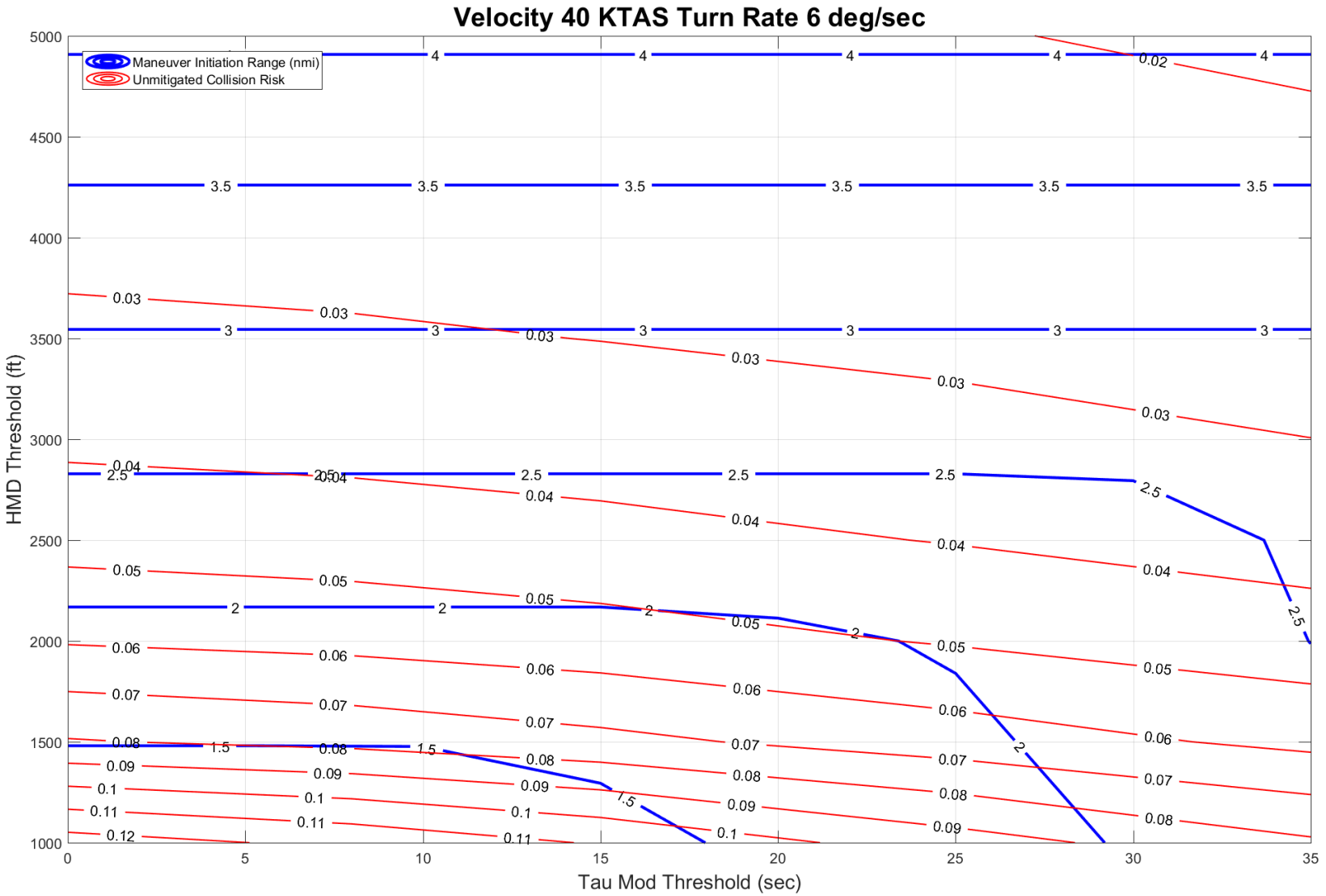


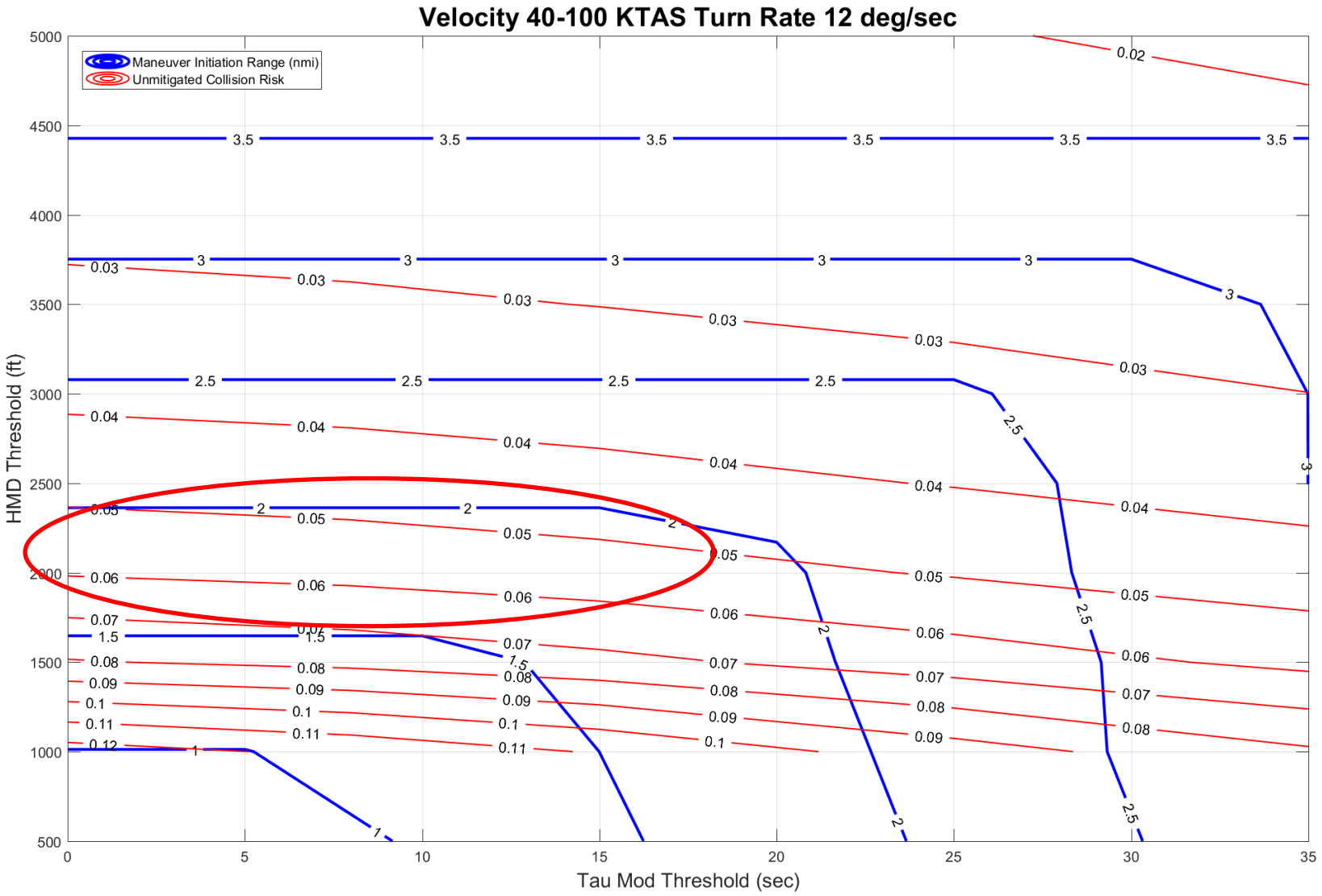
ACES Encounter Filters

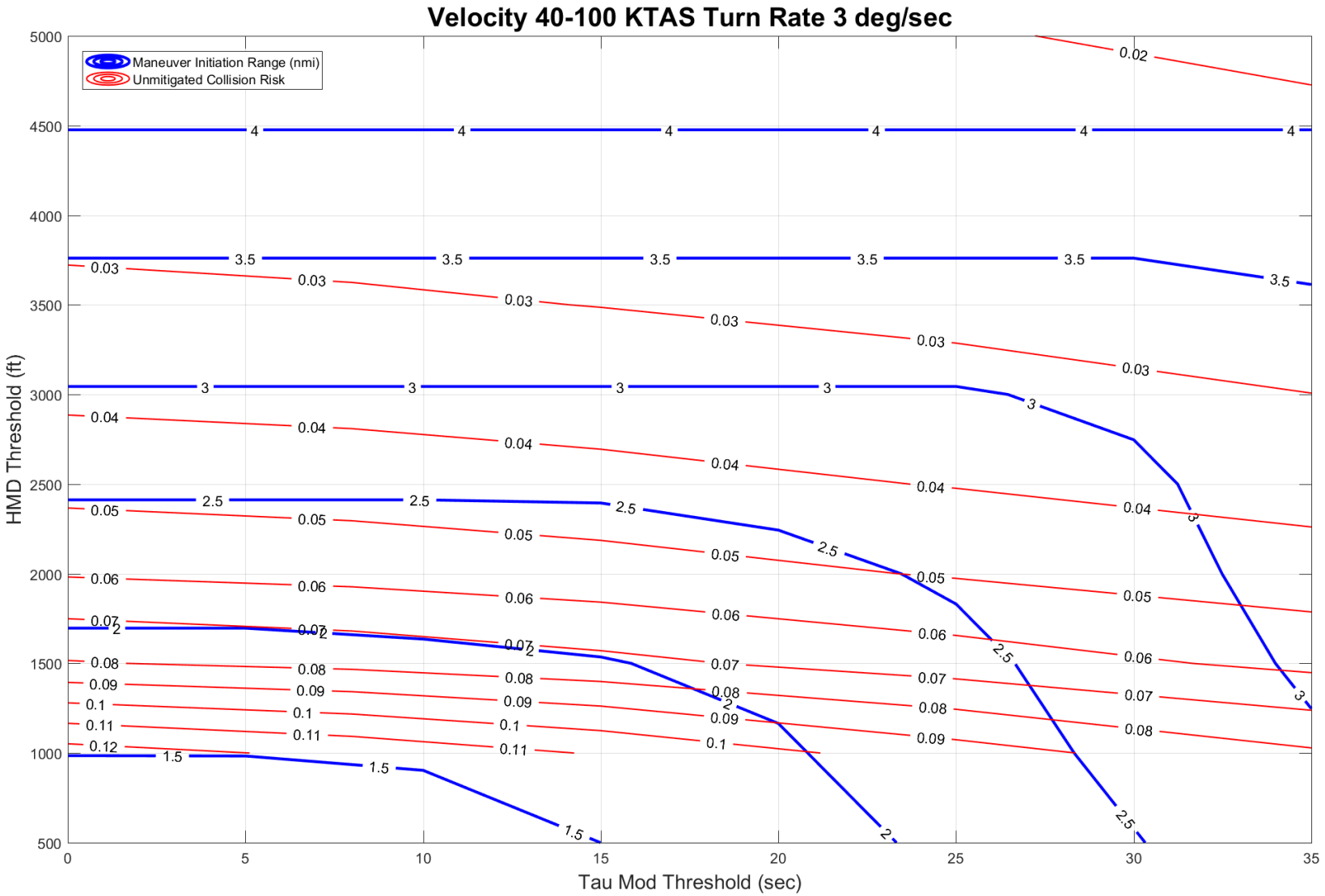
- Criteria
  - Manned aircraft speed: at or below 170 kts
  - UAS speed: between 30 and 100 kts
  - Altitude - at or below 10,000 ft mean sea level (MSL)
  - Altitude – at or above 500 ft MSL

- Additional filters to be implemented
  - Airspace class
  - Altitude - above 500 ft above ground level (AGL)


Velocity 100 KTAS Turn Rate 6 deg/sec
Maneuver Initiation Range (nmi)
Unmitigated Collision Risk
HMD Threshold (ft)
Tau Mod Threshold (sec)
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
5
10
15
20
25
30
35
2
1.5
2.5
3
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12


Velocity 40 KTAS Turn Rate 6 deg/sec
Maneuver Initiation Range (nmi)
Unmitigated Collision Risk
HMD Threshold (ft)
Tau Mod Threshold (sec)
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
5
10
15
20
25
30
35
4
3.5
3
2.5
2
1.5
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12


Velocity 40-100 KTAS Turn Rate 12 deg/sec
Maneuver Initiation Range (nmi)
Unmitigated Collision Risk
HMD Threshold (ft)
Tau Mod Threshold (sec)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
3.5
3
2.5
2
1.5
1
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02


Velocity 40-100 KTAS Turn Rate 3 deg/sec
Maneuver Initiation Range (nmi)
Unmitigated Collision Risk
HMD Threshold (ft)
Tau Mod Threshold (sec)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
4
3.5
3
2.5
2
1.5
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12

Additional Considerations

- Can Phase 1 UAS have an alternative DWC for non-cooperative aircraft? Can a single DWC be defined for both Phase 1 UAS and low C-SWaP UAS (for non-cooperative aircraft)?

Select Simulation Schedule

- Well clear trade study (Fast Time 1)
  - Preliminary Results briefing: December 5, 2017 at SC-228 F2F
  - Final results briefing: February 20, 2017
- Alerting and surveillance uncertainty (Fast Time 2)
  - Planning starts in December 2017
  - Data collection May 2018
  - Final results September 2018
- HITL
  - Planning starts in April 2018
  - Data collection October 2018
  - Final results February 2019
- Closed loop (Fast Time 3)
  - Planning January 2019
  - Data collection June 2019
  - Final results November 2019

VFR Traffic

- 21 days across 4 seasons in 2012 (24 hours each day)

January 2012						
Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

April 2012						
Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

July 2012						
Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

October 2012						
Su	M	Tu	W	Th	F	Sa
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

- ~~Manned IFR data: ASDI (Airspace Situation Display to Industry)~~
- Manned VFR data: 84th Radar Evaluation Squadron (RADES) Air Defense Radar Data
  - Both cooperative and non-cooperative VFR traffic that satisfy speed range (<170 kts) and target airspace (< 10,000 ft and non-terminal operations) will be used

UAS Missions

Number	Mission Types	Airspace	UAS Group	Cruise Altitude	Cruise Speed (KTAS)	Flight Pattern
1	Aerial Imaging and Mapping	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	3000 ft. AGL	44 to 51	Radiator-grid pattern or circular pattern
2	Air Qualtiy Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B (RQ7B)/NASA Sierra	4k, 5k, and 6k ft AGL	74 to 89	Radiator-grid pattern
3	Airborne Pathogen Tracking	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B (RQ7B)/NASA Sierra	3,000 ft., 5,000 ft. and 10,000 ft. AGL	72 to 97	Radiator-grid pattern
4	Flood Inund. Mapping	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	4,000 ft. AGL	46 to 51	Grid pattern
5	Flood Stream Flow	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	4,000 ft. AGL	46 to 51	Grid pattern and/or along stream direction
6	Law Enforcement	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	3,000 ft. AGL	44 to 51	Three types of pattern: 1) grid pattern, 2) random, 3) outward spirial
7	Point Source Emission	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Shadow-B	3,000 ft. AGL	72 to 80	Grid pattern and/or along stream direction
8	Spill Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Shadow-B/Sierra	3,000 ft. to 13,000 ft. AGL	72 to 93	Up and down-wind flights in a radiator-grid pattern, Round-the-clock
9	Tactical Fire Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	ScanEagle/Shadow-B	3,000 ft. AGL	72 to 75	Circular flight path following the perimeter of a wildfire
10	Traffic Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B	1,500 ft. AGL	58 to 84	Geo-spatial monitoring flight path
11	Wildlife Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	3,000 ft. AGL	44 to 51	Radiator-grid pattern
12	News Gathering	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	1,500 ft. to 3,000 ft. AGL	44 to 51	Random-path: e.g., police-chase; Circular orbit:

VFR Intruder Traffic

- It is assumed that unmanned aircraft will be equipped with onboard radar, active surveillance transponder (Mode C/S), and ADS-B surveillance system to detect cooperative and non-cooperative intruder aircraft.

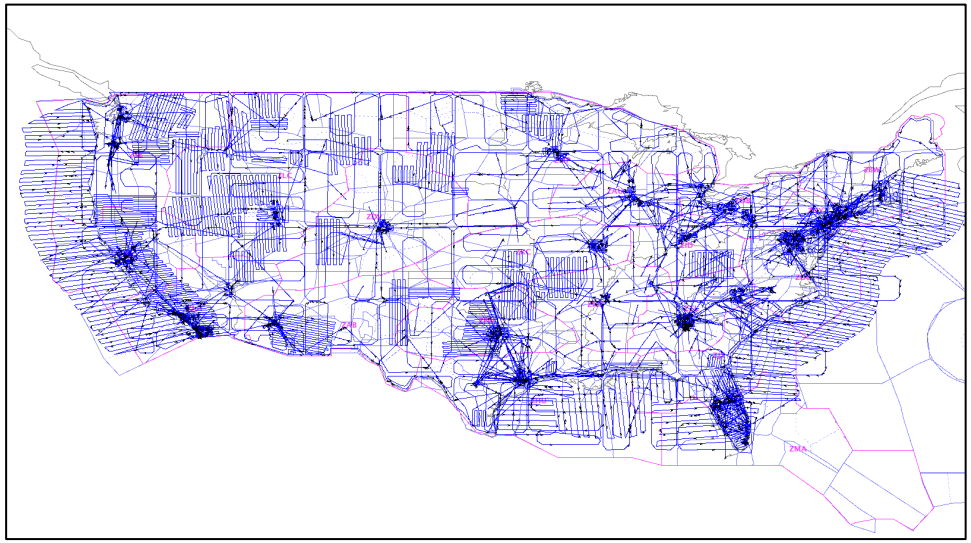
- Types of intruders with different equipage
  - Intruders operating under IFR (Coopeative)
  - Intruders operating under VFR (Cooperative and Non-cooperative)

Intruder Aircraft	Transponder Equipage	Percentage
Cooperative AC 1	ADS-B Out (1090 or UAT)	71%*
Cooperative AC 2	Mode C transponder Only	14%*
Non-Coop AC	No Transponder (or Mode A transponder)	15%*

*Based on OSED document: Table A-1. Intruder Equipage Assumptions Post-2020

Simulation Platform

- Airspace Concept Evaluation System (ACES) and JADEM Fast-time Simulation Framework
  - Simulate NAS-wide air traffic operations of UAS, IFR, and VFR traffic



- Various realistic encounters between UAS and IFR/VFR manned traffic in civil airspace
  - Manned IFR traffic: ASDI (Airspace Situation Display to Industry) data
  - Historical cooperative and non-cooperative VFR traffic
    - The 84th Rader Evaluation Squadron (RADES) data
  - Proposed UAS Flights
    - 12 different types of UAS missions generated by Intelligent Automation Inc.

- UAS DAA Alerting and Guidance System [JADEM]
  - Higher fidelity surveillance model: Honeywell sensor models
  - DAIDALUS DAA alerting and guidance algorithm

Cooperative Traffic